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13. ABSTRACT (Maximum 200 words) Advanced optical diagnostic techniques relevant to propulsion were investigated. The techniques studied were based on laser spectroscopy, with emphasis on spectrally-resolved absorption and laser-induced fluorescence (LIF). Laser sources included tunable cw near-infrared diode lasers and tunable (or fixed-wavelength) pulsed lasers operated at ultraviolet and infrared (IR) wavelengths. The cw lasers were spectrally narrow, allowing study of innovative diagnostics based on spectral line shapes, while the pulsed lasers provided intense bursts of photons needed for techniques based on LIF. Accomplishments of note included: development of new diagnostic methods based on IR planar laser-induced fluorescence (IR-PLIF); demonstration of ultra-sensitive detection of CO through the first use of 2.3-micron diode lasers for combustion applications; initial measurements of absorption and fluorescence properties of 3-pentanone, enabling evaluation of this species as a flow tracer in air-breathing propulsion flowfields; continued development of a novel facility for studies of combustion gas spectroscopy at high pressures; and final development and testing of a new sensor for monitoring velocity in hypervelocity streams via Doppler-shifted absorption of 770 nm diode laser light.			
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on
ADVANCED DIAGNOSTICS FOR REACTING FLOWS
Grant AFOSR F49620-98-1-0010

Prepared for
AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

For the Period
August 1, 1999 to July 31, 2000

Submitted by
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1.0 ABSTRACT

Advanced optical diagnostic techniques relevant to propulsion were investigated. The techniques studied were based on laser spectroscopy, with emphasis on spectrally-resolved absorption and laser-induced fluorescence (LIF). Laser sources included tunable cw near-infrared diode lasers and tunable (or fixed-wavelength) pulsed lasers operated at ultraviolet and infrared (IR) wavelengths. The cw lasers were spectrally narrow, allowing study of innovative diagnostics based on spectral line shapes, while the pulsed lasers provided intense bursts of photons needed for techniques based on LIF. Accomplishments of note included: development of new diagnostic methods based on IR planar laser-induced fluorescence (IR-PLIF); demonstration of ultra-sensitive detection of CO through the first use of 2.3-micron diode lasers for combustion applications; initial measurements of absorption and fluorescence properties of 3-pentanone, enabling evaluation of this species as a flow tracer in air-breathing propulsion flowfields; continued development of a novel facility for studies of combustion gas spectroscopy at high pressures; and final development and testing of a new sensor for monitoring velocity in hypervelocity streams via Doppler-shifted absorption of 770 nm diode laser light.

2.0 TECHNICAL DISCUSSION

2.1 Infrared PLIF Imaging

Infrared (IR) PLIF shows the potential for visualization of important species such as CO, CO₂, CH₄ and H₂O that cannot be visualized using traditional PLIF techniques. In IR PLIF, a tunable IR laser source is used to excite vibrational transitions in molecules, and the resulting vibrational fluorescence is imaged onto an IR camera. Preliminary analytical and experimental results have been obtained which demonstrate the feasibility of IR PLIF for species imaging.

Excitation of CO (2.35 μm) and CO₂ (2.0 μm) followed by collection near 4.3-4.7 μm has been implemented using a high-pulse-energy tunable IR optical parametric oscillator and a gated InSb IR camera. Fig. 1 shows single-shot visualization of the fuel region of a CO diffusion flame (IR PLIF of CO) as well as visualization of mixing of forced CO₂-air jets (IR PLIF of CO₂).

We have also investigated techniques employing vibrational energy transfer to image multiple species using single laser excitation. Fig. 2 shows visualization of both CO (fuel) and CO₂ (fuel-product interface) of a CO-air laminar diffusion flame. Both images are generated using excitation of the R(12) line of the CO 2v band; different collection filters are used to image the resulting fluorescence from either CO or CO₂.

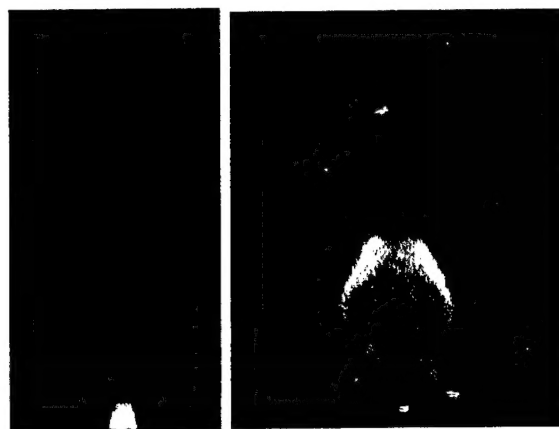


Fig. 1. (a) At left: single-shot visualization of the fuel region of a CO/Ar/H₂ laminar diffusion flame generated using IR PLIF of CO. (b) At right: single-shot visualization of mixing of a forced CO₂/Ar jet in air generated using IR PLIF of CO₂.

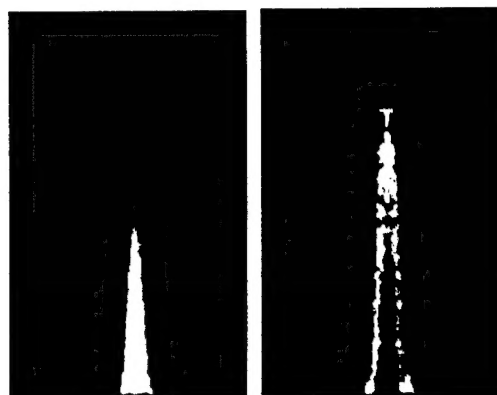


Fig. 2. At left: CO fluorescence from fuel region of a CO/Ar/H₂ laminar diffusion flame after excitation of CO. At right: CO₂ fluorescence (indicating fuel-product interface) from the same flow using *identical laser excitation of CO*.

2.2 Ultra-Sensitive CO Detection

A diode-laser sensor system based on wavelength modulation spectroscopy (WMS) with $2f$ detection has been developed to measure 0.1 ppm-meter levels of carbon monoxide (CO) using a new room temperature diode laser operating near 2.3 microns. The primary feature of WMS techniques is their inherent robustness in hostile environments. Because the absorption signal is obtained from the variation of attenuation with optical frequency rather than the attenuation itself, the technique is immune to background emission noise (e.g., from hot particles) and is insensitive to laser attenuation noise (e.g., beam steering, scattering, and solid- or liquid-phase aerosol absorption). The result is a significant reduction in the noise component of the signal. The availability of 2.3 micron lasers (InGaAsSb) permits selection of strong CO transitions with minimal interference of H₂O absorption (<1%), which is prevalent in combustion environments.

A laboratory demonstration successfully yielded sensitive CO detection at a 50 Hz repetition rate. An atmospheric-pressure C₂H₄-air premixed flame was used to produce combustion products, and the diode laser beam was directed along the centerline of the horizontal exhaust duct (120-cm pathlength) and onto an InAs detector. The laser mean frequency was tuned over the CO R(15) transition by a 50-Hz ramp current modulation while a 33-kHz (f) injection dither current (sinusoidal) was superimposed to obtain wavelength modulation. Fig. 3 illustrates representative lineshapes (20-sweep average) recorded at equivalence ratios of 0.72 and 0.95. The signal-to-noise ratio of these lineshapes is approximately 100 which translates to a detection sensitivity of ~0.1 ppm-m for a repetition rate of 2.5 Hz.

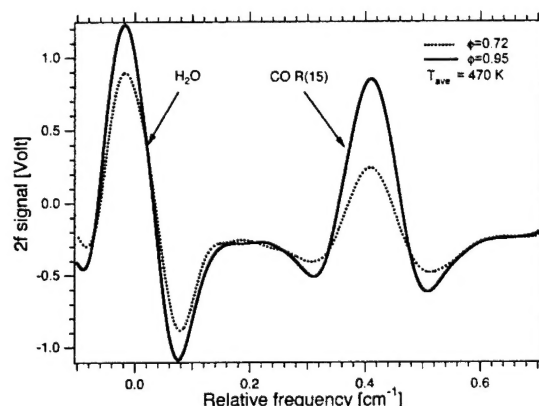


Fig. 3. Representative $2f$ lineshapes (~ 1.46 modulation index, 20-sweep average) for CO measurements in the 120-cm exhaust duct of a laboratory combustor.

2.3 Ketone Photophysics for Quantitative PLIF Diagnostics

Our past studies of acetone (CH₃COCH₃, bp 56 °C) have led to new and useful strategies for instantaneous, 2-D temperature and mixture-fraction diagnostics for gaseous flowfields at atmospheric pressure. More recently, we have begun to extend these diagnostics to flows above atmospheric pressure, i.e. to conditions relevant to the mixing regions in high pressure combustors. In addition, we have continued to search for attractive alternatives to acetone in an effort to optimize current techniques and develop new ones based upon fluorescent and physical behavior. 3-pentanone (C₂H₅COC₂H₅, bp 102 °C) is a candidate with many of acetone's attractive photophysical attributes; furthermore its higher molecular weight makes it better suited for tracking heavier compounds during mixing processes. Also, as shown in Fig. 4, initial experiments performed on 3-pentanone using 248 and 308 nm laser excitation indicate that it is a better temperature indicator than acetone up to 700 K; however, its complex behavior at higher

temperatures may make quantitative imaging problematic. Further studies using other excitation wavelengths should lead to a better understanding of 3-pentanone as well as the potential for other ketones* as tracer candidates.

2.4 High-Pressure Diagnostics

Work has continued on two fronts: development of a new laboratory combustor well-suited for fundamental studies of absorption and fluorescence spectroscopy of gases at high pressures (to 50 atm) and temperatures (2000 K), and exploration of a

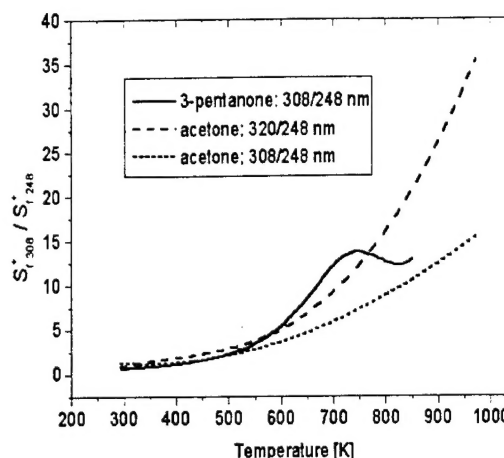


Fig. 4. Comparison of dual-wavelength fluorescence signal ratios from 3-pentanone and acetone – preliminary results. All data come from experiments at atmospheric pressure.

diode-laser absorption diagnostic for H_2O and temperature in high-pressure environments. The new combustor duplicates a German design which has been utilized successfully at these conditions. Construction is complete and the combustor and associated control systems are now undergoing checkout. The associated pulsed dye laser system and associated spectroscopic recording devices are also nearly complete. The high-pressure diode laser absorption diagnostic has been applied to the transient flows in a shock tube, which has allowed convenient variation of pressure, temperature and composition over wide ranges. Experiments up to 65 atm and temperatures to 1800 K have been completed and submitted for publication. Data obtained in the shock tube experiments have provided an important complement to the current HITRAN spectral data base for water vapor.

2.5 TDLAS Probe Enhancement for Hypervelocity Flows

In previous years we reported on diagnostics strategies to measure temperature, velocity, and diode laser absorption spectroscopy (TDLAS) techniques. These measurements were performed using robust probes installed directly in high-enthalpy flowfields and fiber coupled to rapidly tunable laser sources operating at near-IR wavelengths. One system monitored water vapor which is both a contaminant and a combustion product in hydrogen-driven reflected shock tunnels, and

* Ketone – an organic compound containing a carbonyl group (CO) attached to two carbon atoms.

the second monitored potassium, which was found to exist naturally in Calspan's 96" hypersonic shock tunnel and in Stanford's expansion tube facility.

Recent efforts have concentrated on abating potassium absorption in the boundary layer by introducing slot cooling capability to the probe. Fig. 5 shows a schematic of the diode-laser probe with slot injection capability. Additionally, the design incorporates removable optoelectronics enabling measurements of different species and parallel-counter-propagating beams for velocity measurement enhancement.

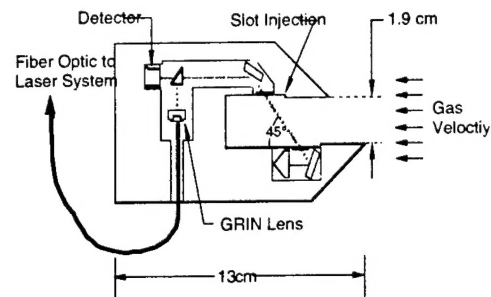


Fig. 5. A schematic of the diode laser probe with slot cooling capabilities and the counter propagating dual-pass optical train to enhance the velocity measurement.

3.0 PUBLICATIONS

3.1 Refereed Publications

E. R. Furlong, R. M. Mihalcea, M.E. Webber, D. S. Baer and R.K. Hanson, "Diode Laser Sensors for Real-Time Control of Pulsed Combustion Systems," *AIAA J.*, **37**, 732-737 (1999).

M.C. Thurber and R.K. Hanson, "Simultaneous Imaging of Temperature and Mole Fraction using Acetone Laser-Induced Fluorescence," *Experiments in Fluids*, submitted 1/99.

S.D. Wehe, D.S. Baer and R.K. Hanson, "Diode-Laser Sensor for Velocity Measurements in Hypervelocity Flows," *AIAA J.* **37**, 1013-1015 (1999).

M.C. Thurber and R.K. Hanson, "Pressure and Composition Dependence of Acetone Laser Induced Fluorescence with Excitation at 248, 266 and 308 nm," *Appl. Physics B* **69**, 229-240 (1999).

V. Nagali, J.T. Herbon, D.C. Horning, D.F. Davidson and R.K. Hanson, "Shock Tube Study of High-Pressure H₂O Spectroscopy," *Appl. Optics* **38**, 6942-6950 (1999).

D. F. Davidson and R. K. Hanson, "Spectroscopic Diagnostics," in *Handbook of Shock Waves*, Chapter 4.2, G. Ben-Dor, T. Elperin, O. Igra, eds., in press.

B.J. Kirby and R.K. Hanson, "Planar Laser-Induced Fluorescence Imaging of Carbon Monoxide using Vibrational (Infrared) Transitions," *Appl. Physics B* **69**, 505-507 (1999).

G. Totschnig, D.S. Baer, J. Wang, F. Winter, H. Hofbauer and R.K. Hanson, "Multiplexed Continuous-Wave Diode-Laser Cavity Ring-Down Measurements of Multiple Species," *Appl. Optics*, **39**, 2009-2016 (2000).

B.J. Kirby and R.K. Hanson, "Infrared PLIF Imaging of CO and CO₂," *28th Symp. (International) on Combustion*, Edinburgh, Scotland, July 2000, accepted.

J. Wang, M. Maiorov, D.S. Baer, D.Z. Garbuzov, J.C. Connolly and R. K. Hanson, "In Situ Measurements of CO using Diode Laser Absorption near 2.3 microns," *Appl Optics*, in press.

A.Ben-Yakar and R.K. Hanson, "Characterization of Expansion Tube Flows for Hypervelocity Combustion Studies in the Flight Mach 8-13 Engine," *J. Prop. and Power*, submitted May 2000.

J. Wang, S. T. Sanders, J. B. Jeffries and R. K. Hanson, "Oxygen Measurements at High Pressures using Vertical Cavity Surface-Emitting Lasers," *App. Phys. B.*, submitted July 2000.

3.2 Presentations

J. D. Koch and R. K. Hanson, "Ketone Photophysics for Quantitative PLIF Imaging," paper AIAA-2000.....at 39th Aerospace Sciences Meeting, Reno, NV, January 2000.

D. S. Baer, S. Sanders, S. Wehe and R.K. Hanson, "Diode-Laser Absorption sensors for Realtime *in situ* Measurements," invited presentation at OSA Annual Meeting, Santa Clara, CA, October 1999.

B. J. Kirby and R. K. Hanson, "Dual-Camera Infrared PLIF Imaging of CO and CO₂," paper AIAA 2000-0640 at AIAA Aerospace Sciences Meeting, Reno, NV, January 2000.

M. E. Webber, S. Kim, D. S. Baer and R.K. Hanson, "In Situ Combustion Measurements of CO₂ using Diode Laser Sensors Near 2.0 μm ," paper AIAA 2000-0775 at AIAA Aerospace Sciences Meeting, Reno, NV, January 2000.

4.0 PERSONNEL

Individual researchers partially or fully supported by the program during the reporting period are listed below. All the work has been carried out in the High Temperature Gasdynamics Laboratory, in the Department of Mechanical Engineering, under the supervision of Professor R. K. Hanson.

4.1 Postdoctoral Research Associates

Doug Baer
Tom Jenkins
Jay Jeffries

4.2 Graduate Research Associates

Adela Ben-Yakar
Shawn Wehe
Brian Kirby
Jian Wang
Jon Koch

4.3 Ph.D Degrees Awards (1999-2000)

Adela Ben-Yakar, "Experimental Investigation of Mixing and Ignition of Transverse Jets in Supersonic Crossflows"

Shawn Wehe, "Development of a Tunable Diode Laser Probe for Measurements in Hypervelocity Flows"

5.0 SIGNIFICANT INTERACTIONS

In addition to the interactions associated with the presentations and publications listed in Section we have had numerous visitors to our laboratory during this past year. Foreign visitors have come from Germany, China, Australia, and Japan; industrial and national laboratory visitors have included representatives from Aerometrics, Physical Sciences, Inc., United Technologies, Metrolaser, NASA Ames, NASA Lewis, Boeing, and Sandia (Albuquerque and Livermore). Also during this period, Professor Hanson has given invited presentations on AFOSR-sponsored diagnostics research to several industrial laboratories, universities, and government groups. Members of our group have provided technical information and advice, by telephone and mail, to several external researchers interested in duplicating or extending our diagnostics concepts.

6.0 INVENTIONS

None.

7.0 TECHNOLOGY TRANSITIONS/TRANSFERS

7.1 PLIF Imaging in Rocket Exhaust

Performer: R. K. Hanson, Stanford University (650-723-1745)
Customer: Dr. Larry Cohen, Aerojet Corporation, Sacramento, CA (916-355-5182)
Result: Species concentration imaging in liquid rocket engines
Application: Data confirming suspected oxidizer nonuniformity in Titan IV stage 1 engine

7.2 IR Imaging for Joint Strike Fighter

Performer: R. K. Hanson, Stanford University (650-723-1745)
Customer: Kondala Saripalli, Boeing Corp., St Louis, MO (314-234-9933)
Result: CO₂ imaging strategies
Application: Hot gas ingestion monitoring during landing of STOVL Joint Strike Fighter

7.3 Water Vapor and Oxygen Measurements

Performer: R. K. Hanson, Stanford University (650-723-1745)
Customer: Dr. Mark Allen, Physical Sciences, Inc., Andover, MA (978-689-0003)
Result: Multiplexed laser measurements of O₂, H₂O and temperature
Application: Development of commercial diode laser sensors for industrial furnaces

7.4 Spectroscopic Data for Ammonia

Performer: R.K. Hanson, Stanford University (650-723-1745)
Customer: Peter deBarber, Metrolaser, Irvine, CA (949-553-0688)
Result: Multiplexed laser absorption measurements of species and temperature
Application: Diode laser and Fiberoptic sensors for industrial process measurement and control

7.5 PLIF Imaging in SCRAMJETS

Performer: R. K. Hanson, Stanford University (650-723-1745)
Customer: Dr. Campbell Carter, Innovative Sci. Sol., Inc., Dayton, OH (937-255-8704)
Result: Physics of planar-laser-induced fluorescence of species and temperature
Application: Work at WPAFB: OH PLIF in hydrocarbon SCRAMJET flowfield to determine location/extent of burning region

7.6 PLIF Imaging in Flames

Performer: R. K. Hanson, Stanford University (650-723-1745)
Customer: Dr. Campbell Carter, Innovative Sci. Sol., Inc., Dayton, OH (937-255-8704)
Result: Physics of planar-laser-induced fluorescence of species and temperature
Application: Work at WPAFB: OH/CH PLIF in nonpremixed flames for CFD code validation

8.0 PIADC SURVEY FORMS

Principal Investigator Annual Data Collection (PIADC) Survey Form

Please submit requested data for the Period 1 October 1999 through September 2000. Request you follow the data requirement and format instructions below. This data is due to your AFOSR program manager NLT 30 September 2000.

NOTE: If there is insufficient space on this survey to meet your data submission, please submit additional data in the same format as identified below.

PI DATA

Name(last,First,MI) HANSON, RONALD K.

AFOSR USE ONLY

Project/Subarea

Institution: Stanford University

Contract/Grant No.: AFOSR F49620-98-1-0010

NX _____

FY _____

NUMBER OF CONTRACT/GRANT CO-INVESTIGATORS

Faculty 1 Post doctorates 3 Graduate Student 5 Other _____

PUBLICATIONS RELATED TO AFOREMENTIONED CONTRACT/GRANT

Name of Journal, Book, etc: *AIAA J.*

Title of Article: Diode Laser Sensors for Real-Time Control of Pulsed Combustion

Author(s): E. R. Furlong, R. M. Mihalcea, M. E. Webber, D. S. Baer and R. K. Hanson

Publisher (if applicable): _____

Volume: 37 Page(s): 732-737 Month Published: _____ Year Published: 1999

Name of Journal, Book, etc: *Experiments in Fluids*

Title of Article: Simultaneous Imaging of Temperature and Mole Fraction using Acetone Laser-Induced Fluorescence

Author(s): M. C. Thurber and R.K. Hanson

Publisher (if applicable): _____

Volume: _____ Page(s): _____ Month Published: _____ Year Published: in press

Name of Journal, Book, etc: *AIAA J.*

Title of Article: Diode-Laser Sensor for Velocity Measurements in Hypervelocity Flows

Author(s): S. D. Wehe, D. S. Baer and R.K. Hanson

Publisher (if applicable): _____

Volume: 37 Page(s): 1013-1015 Month Published: _____ Year Published: 1999

Name of Journal, Book, etc: *Appl. Physics B*

Title of Article: Pressure and Composition Dependence of Acetone Laser Induced Fluorescence with Excitation at 248, 266 and 308 nm

Author(s): M. C. Thurber and R. K. Hanson

Publisher (if applicable): _____

Volume: 69 Page(s): 229-240 Month Published: _____ Year Published: 1999

Name of Journal, Book, etc: *Appl. Optics*

Title of Article: Shock Tube Study of High-Pressure H₂O Spectroscopy

Author(s): V. Nagali, J.T. Herbon, D. C. Horning, D.F. Davidson and R. K. Hanson

Publisher (if applicable): _____

Volume: 38 Page(s): 6942-6950 Month Published: _____ Year Published: 1999

Name of Journal, Book, etc: *Handbook in Shock Waves*

Title of Article: Spectroscopic Diagnostics, Chapter 4.2

Author(s): D. F. Davidson and R.K. Hanson

Publisher (if applicable): G. Ben-Dor, T. Elperin, O. Igra, eds

Volume: _____ Page(s): _____ Month Published: _____ Year Published: in press

Name of Journal, Book, etc: *Appl. Physics B*

Title of Article: Planar Laser-Induced Fluorescence Imaging of Carbon Monoxide using Vibrational (Infrared) Transitions

Author(s): B. J. Kirby and R. K. Hanson

Publisher (if applicable): _____

Volume: 69 Page(s): 505-507 Month Published: _____ Year Published: 1999

Name of Journal, Book, etc: *Appl. Optics*

Title of Article: Multiplexed Continuous-Wave Diode-Laser Cavity Ring-Down Measurements of Multiple Species

Author(s): G. Totschnig, D. S. Baer, J. Wang, F. Winter, H. Hofbauer and R. K. Hanson

Publisher (if applicable): _____

Volume: 39 Page(s): 2009-2016 Month Published: _____ Year Published: 2000

Name of Journal, Book, etc: *28th Symp (International) on Combustion*

Title of Article: Infrared PLIF Imaging of CO and CO₂

Author(s): B. J. Kirby and R. K. Hanson

Publisher (if applicable): _____

Volume: _____ Page(s): _____ Month Published: _____ Year Published: in press

Name of Journal, Book, etc: *Appl. Optics*

Title of Article: In Situ Measurements of CO using Diode Laser Absorption near 2.3 microns

Author(s): J. Wang, M. Maiorov, D. S. Baer, D. Z. Garbuzov, J. C. Connolly and R.K. Hanson

Publisher (if applicable): _____

Volume: _____ Page(s): _____ Month Published: _____ Year Published: in press

Name of Journal, Book, etc: *J. Prop and Power*

Title of Article: Characterization of Expansion Tube Flows for Hypervelocity Combustion Studies in the Flight Mach 8-13 Engine

Author(s): A. Ben-Yakar and R. K. Hanson

Publisher (if applicable): _____

Volume: _____ Page(s): _____ Month Published: _____ Year Published: in press

Name of Journal, Book, etc: *App Physics B*

Title of Article: Oxygen Measurements at High Pressures using Vertical Cavity Surface-Emitting Lasers

Author(s): J. Wang, S. T. Sanders, J.B. Jeffries and R. K. Hanson

Publisher (if applicable): _____

Volume: _____ Page(s): _____ Month Published: _____ Year Published: submitted 7/2000

9.0 HONORS/AWARDS RECEIVED DURING CONTRACT/GRANT LIFETIME

Include: All honors and awards received during the lifetime of the contract or grant, and any life achievement honors such as (Nobel prize, honorary doctorates, and society fellowships) prior to this contract or grant.

Do not include: Honors and awards unrelated to the scientific field covered by the grant/contract.

Honor/Award: Fellow of Optical Society of America Year Received: 1994
Honor/Award Recipient (s): R. K. Hanson
Awarding Organization: Optical Society of America

Honor/Award: Aerodynamic Measurement Technology award Year Received: 1996
Honor/Award Recipient (s): R. K. Hanson
Awarding Organization: American Institute of Aerodynamics and Astronautics (AIAA)

Honor/Award: Best Paper Award: Joint Propulsion Conference (Ground Test TC) Year Received: 1997
Honor/Award Recipient (s): R. M. Mihalcea, D. S. Baer and R. K. Hanson
Awarding Organization: American Institute of Aerodynamics and Astronautics (AIAA)

Honor/Award: AIAA Fellow Year Received: 1997
Honor/Award Recipient (s): R. K. Hanson
Awarding Organization: American Institute of Aerodynamics and Astronautics (AIAA)

Honor/Award: Featured Scientist in Naval Research Review Year Received: 2000
Honor/Award Recipient (s): R. K. Hanson
Awarding Organization: Office of Naval Research